Unlocking time-dependent *CP* violation without signal vertexing at *B* factories

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Based on [Phys.Rev.D 112 (2025) 3, 032011]() by M. Dorigo[1], S. Raiz[2], D. Tonelli[1], R. Ž.[1]

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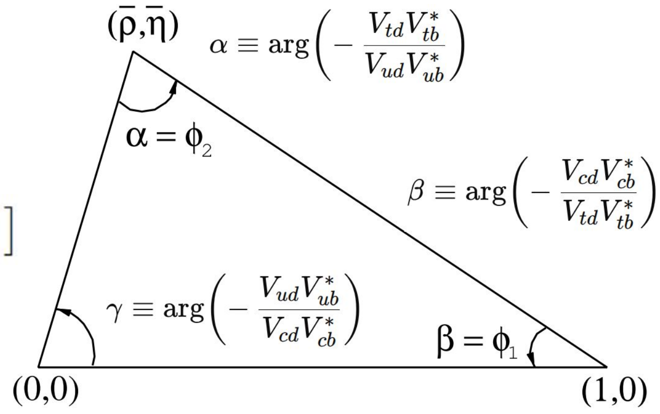
Mixing-induced *CP* violation in B^0 decays

Mixing-induced CP asymmetry ***S*** stems from interference between $B^0 \to B^0_{CP}$ amplitude and $B^0 \to \bar{B}^0 \to B^0_{CP}$ amplitudes, where in the second case B^0 meson first oscillated into $\bar{B}^0$ state.



$$\Gamma\left(B^0/\bar{B}^0(t) \to B^0_{CP}\right) \propto e^{-t/\tau_B}\ \left[1 + q\left(S\sin(\Delta m_d t) - C\cos(\Delta m_d t)\right)\right]$$

Mixing-induced *CP* asymmetry

Direct *CP* asymmetry

At e^+e^- B factories time integrated measurements are only sensitive to direct CP asymmetry *C*
→ Need for time-dependent CPV analysis to measure ***S***

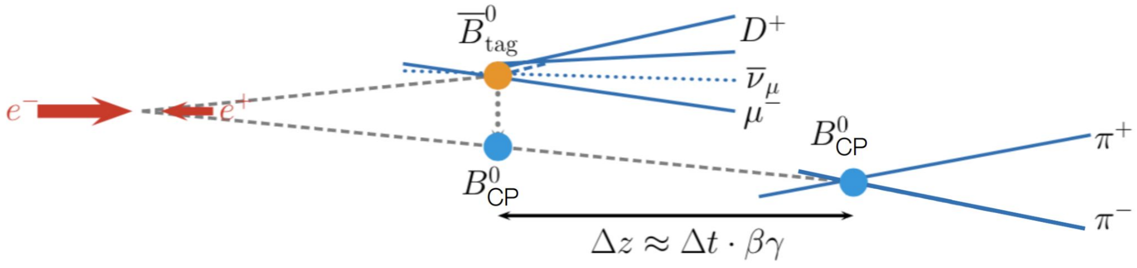
CKM angle	Main channel	Time-dependent?
β	$B^0 \to J/\psi\, K_S$	Yes
α	$B \to \pi\pi,\ \rho\rho,\ \rho\pi$	Yes
γ	$B^\pm \to DK^\pm$	No

Time-dependent CPV analysis is crucial to determine CKM angles α and β.

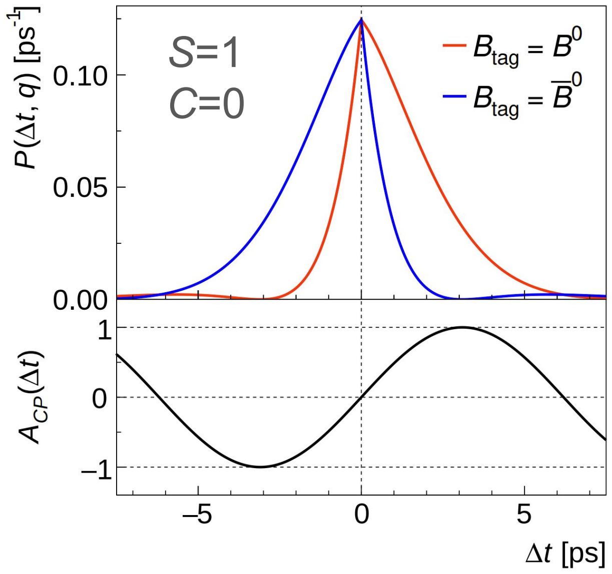
A classical time-dependent CPV measurement

- At e^+e^- *B* factories with asymmetric beam energies (BaBar, Belle, Belle II), the time-dependent CPV is measured in $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0_{CP}\, B^0_{\rm tag}$
- *B* mesons are produced nearly at the rest in CM frame and they are drifted in the direction of electron beam
- B^0_{CP} decays to *CP* eigenstate of interest
- $B^0_{\rm tag}$ decays inclusively & its flavor (B^0 or $\overline{B}^0$) is determined by the flavor tagger

$$\mathcal{A}_{CP}(\Delta t) = \frac{\mathcal{P}(\Delta t, +1) - \mathcal{P}(\Delta t, -1)}{\mathcal{P}(\Delta t, +1) + \mathcal{P}(\Delta t, -1)}$$
$$= S \sin \Delta m \Delta t - C \cos \Delta m \Delta t$$



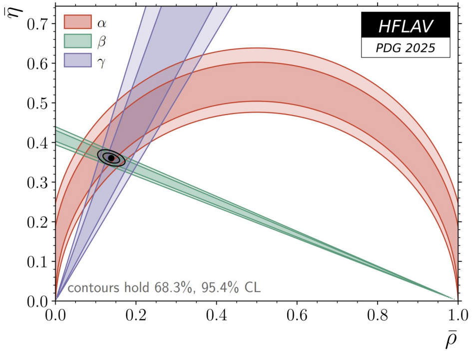
$\Delta t = t_{CP} - t_{tag}$



Both vertices are required!

Some channels were out of scope…

- S from $B^0 \to \pi^0\,\pi^0$ (i.e. 4-photon state) sensitive to CKM angle α is the standard example
- Missing S measurement in $B^0 \to \pi^0\pi^0$ leads to 8-fold ambiguity in the α measurement from $B \to \pi\,\pi$

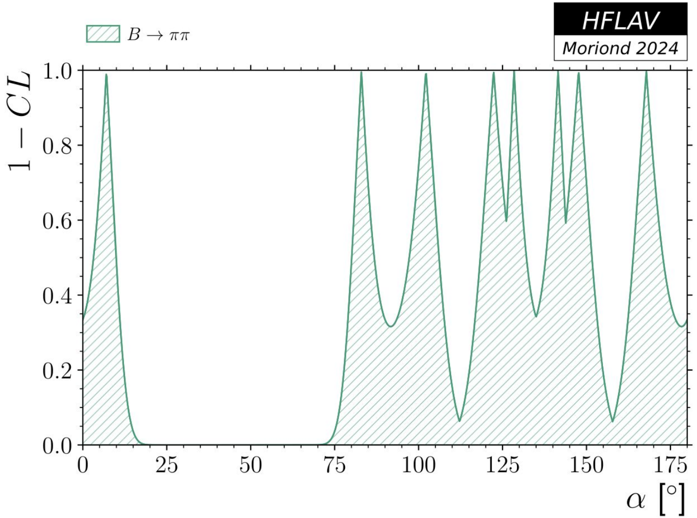


The physics of B factories (2014)

$B \to \pi\pi$ system is complicated by the need to measure time-dependent CP asymmetry of the all-neutral final state decay of B^0 mesons to $\pi^0\pi^0$. This is not possible at the present level of statistics, although high luminosity super flavor factory may be able to constrain the decay vertex of the $B^0 \to \pi^0\pi^0$ candidate using Dalitz decays of one or both π^0 mesons, or events where one or more photons convert in the detector material. The situation is further exac-

Belle II physics book (2018)

$B^0 \to \pi^0\pi^0$. At present, there is not enough data to perform a time-dependent CP-analysis of the decay mode $B \to \pi^0\pi^0$. Neutral pions decay to about (98.823 ± 0.034)% [88] into two photons, and, without external photon conversion $\gamma \to e^+ e^-$, they do not provide information to reconstruct the vertex of the B^0. Also the fraction of useful Dalitz decays



Getting signal B_{CP} vertex from "rare" $\pi^0 \to e^+e^-\gamma$ or from $\gamma \to e^+e^-$ conversion requires high luminosity and it is not feasible with current luminosity of B factories.

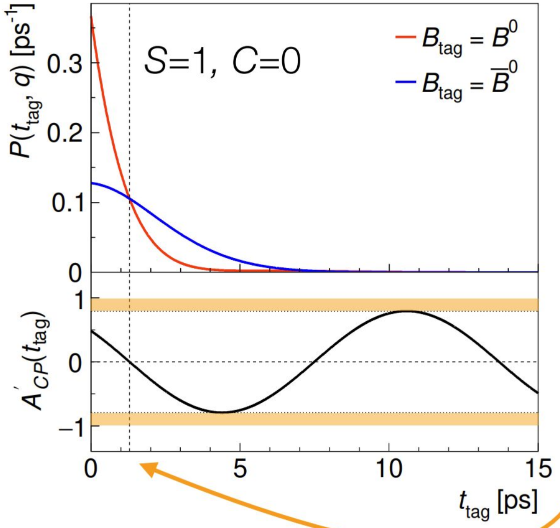
Let's do it without signal B_{CP} vertex!

The time-dependent flavour asymmetry appears even when measuring a single time, e.g. t_{tag}, instead of $\Delta t = t_{CP} - t_{tag}$

$$\mathcal{P}(t_{\rm tag}, t_{CP}, q) = \frac{e^{-\frac{t_{CP}+t_{\rm tag}}{\tau}}}{2\tau^2}\Big(1 + q\big[S\sin\Delta m(t_{CP} - t_{\rm tag}) - C\cos\Delta m(t_{CP} - t_{\rm tag})\big]\Big)$$

Marginalizing over t_{CP}

$$\mathcal{P}(t_{\rm tag}, q) = \frac{e^{-t_{\rm tag}/\tau}}{2\tau}\Big(1 + q\big[S'\sin\Delta m(t_{\rm tag} - \hat{t}\,) - C'\cos\Delta m(t_{\rm tag} - \hat{t}\,)\big]\Big),$$



$$\mathcal{A}'_{CP}(t_{\rm tag}) = S'\sin\Delta m(t_{\rm tag} - t_0) - C'\cos\Delta m(t_{\rm tag} - t_0)$$

$$S' = -\frac{S}{\sqrt{1 + (\tau\Delta m)^2}} \approx \mathbf{-0.8}\ \boldsymbol{S}$$

$$C' = \frac{C}{\sqrt{1 + (\tau\Delta m)^2}} \approx \mathbf{0.8}\ \boldsymbol{C}$$

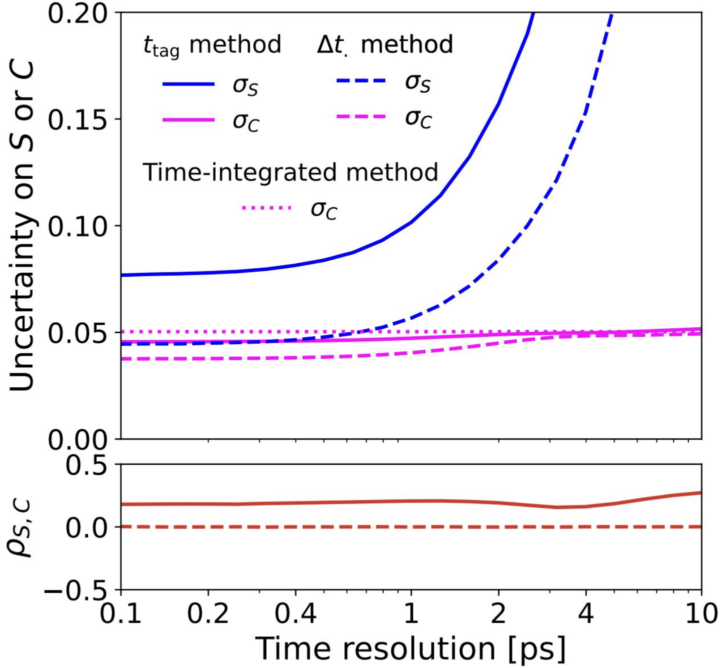
$$t_0 = \frac{1}{\Delta m}\arctan(\Delta m\tau) \approx \mathbf{1.3\ ps}$$

What t_{tag} resolution is needed for measuring S?

Relation between the time resolution and *S* & *C* precision

- Even with perfect time resolution, the usage of only one decay time, instead Δt leads to 70% worse precision of *S*, due to:
    - Smaller amplitude of oscillations
    - Maximal flavor asymmetry appearing at higher t_{tag}, where fewer mesons are undecayed
- A sharp increase of *S* uncertainty for time resolution ~1 ps for both methods
- The t_{tag} method has 20% correlation between *S* & *C* while correlation in Δt method is negligible

For 1000 events with perfect flavor tagging



Can we measure t_{tag} with useful resolution (≈1 ps)?

Measurement of t_{tag}

The t_{tag} measurement at *B* factories exploits:

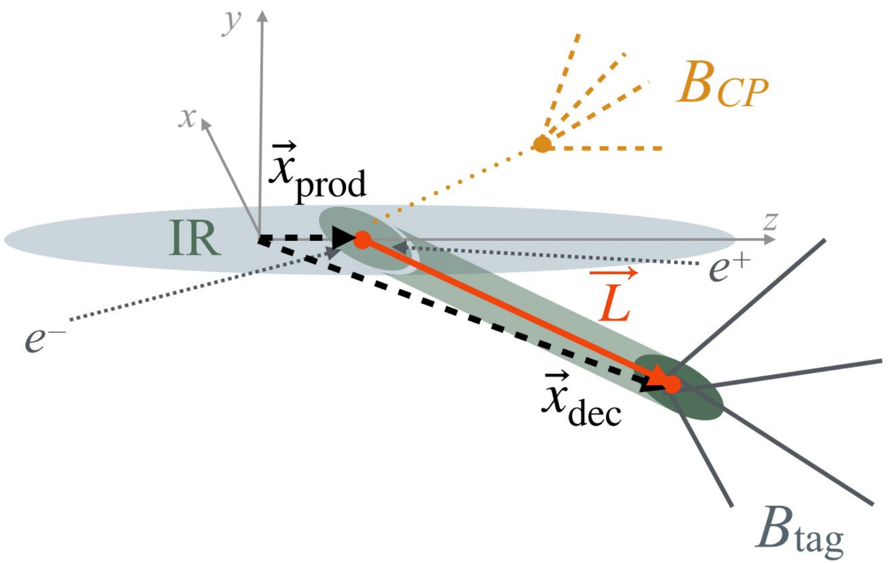
- The spatial distribution of the B_{tag} production point ("beam spot" measured in ee→μμ)
- B_{tag} decay point (=vertex)
- The knowledge of the B_{tag} momentum which is calculated from the B_{sig} momentum using momentum conservation

Vertex fit with beam spot and B_{tag} momentum constraint:

$$\chi^2 = (\vec{x}_{\mathrm{prod}} - \vec{x}_{\mathrm{IR}})^T \boxed{V_{\mathrm{IR}}^{-1}} (\vec{x}_{\mathrm{prod}} - \vec{x}_{\mathrm{IR}}) + (\vec{x}_{\mathrm{dec}} - \vec{x}_{B_{\mathrm{tag}}})^T \boxed{V_{B_{\mathrm{tag}}}^{-1}} (\vec{x}_{\mathrm{dec}} - \vec{x}_{B_{\mathrm{tag}}})$$

$$\boxed{\vec{x}_{\mathrm{dec}} = \vec{x}_{\mathrm{prod}} + \frac{t_{\mathrm{tag}}}{m_B}\vec{p}_{\mathrm{tag}}}$$

$$t_{\mathrm{tag}} = m_B \frac{\vec{L} \cdot \vec{p}_{\mathrm{tag}}}{|p_{\mathrm{tag}}|^2}$$



Determination of both t_{tag} and its uncertainty, exploiting all information we have

Expected t_{tag} resolution at *B* factories

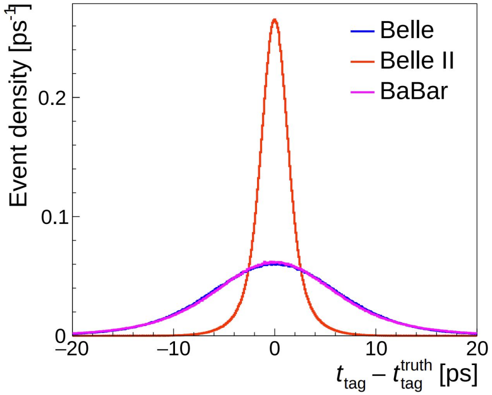
- The t_{tag} resolution depends on the
  - beam spot size
  - beam momenta (direction & energies)
  - B_{tag} vertex resolution
- We implemented a toy model which incorporates all these ingredients for Belle, Belle II and Babar

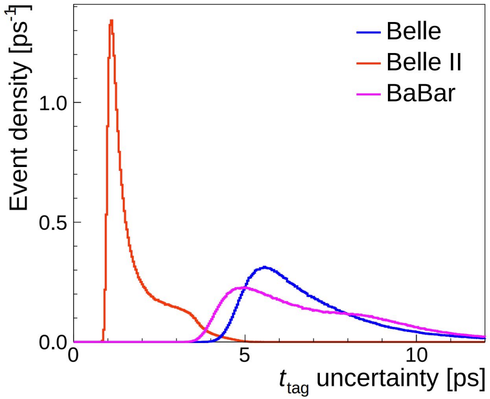
Momenta of beams

IP size

vtx resolution

	Belle II	Belle	BaBar
e^- (e^+) beam energy [GeV]	7.0 (4.0)	8.0 (3.5)	9.0 (3.0)
Beam energy spread [MeV]	5.45	5.36	4.63
Crossing angle [mrad]	83	22	0
Interaction region x width [μm]	13	70	148
Interaction region y width [μm]	0.2	1.0	6.9
Interaction region z width [μm]	350	6000	15150
$B_{\rm tag}$ vertex x-y resolution [μm]	30	80	80
$B_{\rm tag}$ vertex z resolution [μm]	30	100	125





Belle II has reasonable (1.5 ps) t_{tag} resolution, while Belle/Babar resolution of 6 ps hinders any *S* measurement

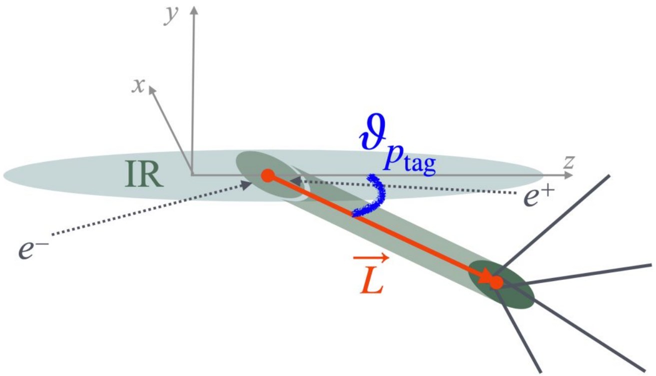
Why Belle II performs so much better?

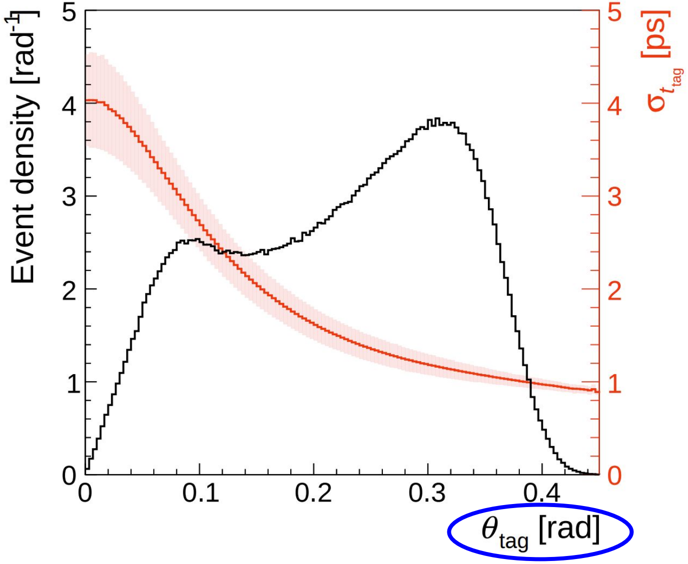
The limiting factor is the determination of the B_{tag} production point
(geometrically it is an intersection of two tubes)

Belle II is superior in

- Transverse size of interaction area (IP tube) (13um vs 70um)
- B_{tag} vertex resolution (B_{tag} tube) (30um vs 80um)
- Angular separation between the IP tube and B_{tag} tube

$$\sigma_t \approx \frac{\sqrt{\sigma_{\mathrm{IR}_\perp}^2 + \sigma_{\mathrm{vtx}}^2}}{c(\beta\gamma)_{\mathrm{tag}} \sin\theta_{p_{\mathrm{tag}}}}$$





Feasibility of S measurement for $B^0 \to \pi^0\pi^0$ at Belle II

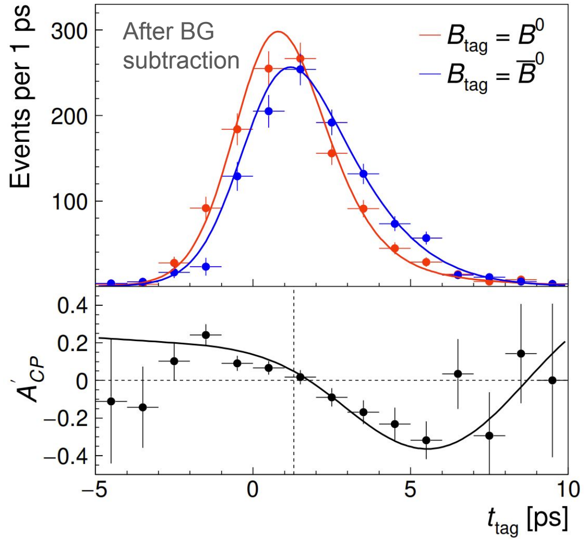
- Real-world scenario, where the $B^0 \to \pi^0\pi^0$ yield, background yield and the shapes of the fitted spectra are taken from existing time-independent Belle II measurement (0.36 ab^{-1}, 125±20 signal decays) Phys.Rev.D 111 (2025) 7, L071102
- Identical fitting strategy is followed as in existing Belle II analysis, but t_{tag} and $\sigma(t_{tag})$ variables are added to the maximum likelihood fit

$$\mathcal{P}_s(t_{\rm tag}, \sigma_{t_{\rm tag}}; q, w) = \frac{e^{-t'_{\rm tag}/\tau}}{2\tau}\Big(1 + q(1-2w)\big[S' \sin\Delta m(t'_{\rm tag} - \hat{t}) - C' \cos\Delta m(t'_{\rm tag} - \hat{t})\big]\Big) \otimes \mathcal{R}_{\sigma_{t_{\rm tag}}}(t_{\rm tag} - t'_{\rm tag})$$

Sample size $[\mathrm{ab}^{-1}]$	$t_{\rm tag}$ $\sigma_{S_{00}}$	$t_{\rm tag}$ $\sigma_{C_{00}}$	Δt $\sigma_{S_{00}}$
0.36	0.75	0.27	–
5.0	0.18	0.07	–
50.0	0.06	0.02	0.28

Δt method based on $\pi^0 \to e^+e^-\gamma$ (projection from Belle II physics book)

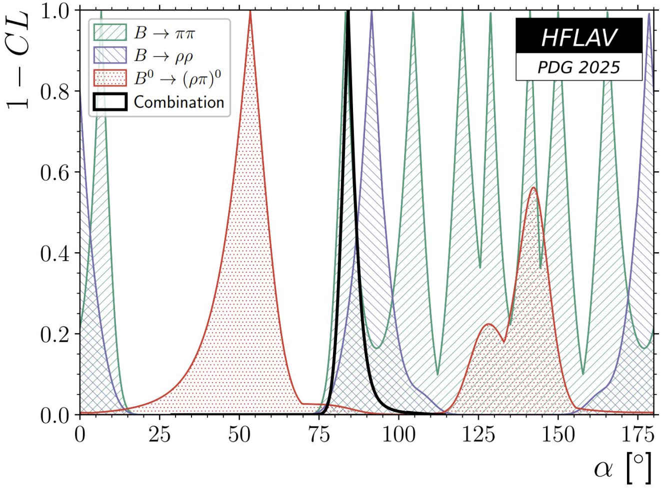
50 ab^{-1}, S=0.65, C=0

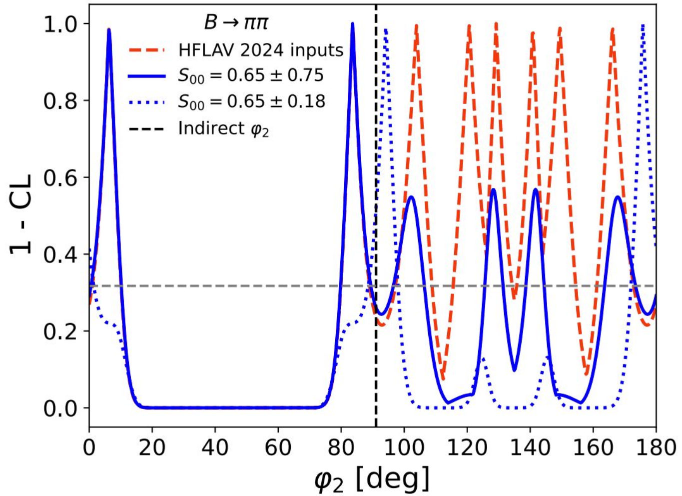


The t_{tag} method has 4 times smaller uncertainty than existing Δt method.

Impact on α

- The CKM angle α is obtained from branching fractions BRs and *CP* asymmetries (S and C) in all isospin combinations of $B \to \pi\pi$ (Gronau-London method)
(α can be also determined from $B^0 \to (\rho\pi)^0$ and $B \to \rho\rho$)
- So far only $S_{\pi+\pi-}$ was measured, which leads to 8-fold ambiguity in α determined from $B \to \pi\pi$ modes





Current Belle II dataset
S_{00} = 0.65±0.75

5 ab^{-1} Belle II dataset
S_{00} = 0.65±0.18

The S_{00} measurement has substantial impact on α determination even with current Belle II data set.

Conclusion

- The t_{tag} method unlocks time-dependent *CP* violation measurement even when B_{CP} vertex is not available
- Unique to Belle II
- The method probed for $B^0 \to \pi^0 \pi^0$ decay
  → 4 times better precision than existing approach
  → Possibility of measuring *S* even with current Belle II dataset with sizable impact on α determination
- Method is also considered for processes like
  $B^0 \to K_{S,L}\, \pi^0$, $B^0 \to \gamma\gamma$ or $B^0 \to K_S\, \nu\, \nu$

Idea pioneered by Andrew Foland

- The single-time time-dependent CPV measurement was first proposed by A. Foland from CLEO in 1999 and we rediscovered it 26 years later
- The main motivation was possible t_{CP}-based sin 2β measurement in $B^0 \to J/\psi\, K_S$ at CLEO
- Possibility for t_{tag}-based measurement of α in $B^0 \to \pi^0\pi^0$ was also mentioned although this channel had not been discovered yet

PHYSICAL REVIEW D, VOLUME 60, 111301

Measurement of *CP* violation at the $\Upsilon(4S)$ without time ordering or Δt

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I derive the expressions for the CP-violating asymmetry arising from interference between mixed and direct decays in the $\Upsilon(4S)$ system, for the case in which only one of the B decay times is observed, integrating over the decay time of the other B. I observe that neither the difference of the decay times Δt, nor even their time ordering, need be detected. A technique for measurement of the CP-violating weak decay parameter sin 2β is described which exploits this observation. [S0556-2821(99)50521-3]

Likely due to non applicability for Belle & BaBar the method was mostly forgotten.